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THESIS

COMPARING THE CAPABILITIES AND PERFORMANCE OF THE ULTRA HIGH FREQUENCY FOLLOW-ON SYSTEM WITH THE MOBILE USER OBJECTIVE SYSTEM

by

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June 2011

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The Mobile User Objective System (MUOS) is the DoD's next generation military Ultra High Frequency (UHF) Satellite Communication (SATCOM) system being designed to augment and eventually replace the currently oversubscribed UHF Follow-On (UFO) System. MUOS adapts a commercial third generation (3G) Wideband Code Division Multiple Access (WCDMA) cellular phone network architecture and combines it with geosynchronous satellites (in place of cell towers) with the goal of providing a more capable UHF SATCOM system.

This research aims at investigating the differences between the legacy UFO and MUOS systems in terms of network performance and quality of service. Using modeling and simulation of both systems against input traffic loads of a hypothetical Joint Task Force, a comparative study of the performance and capabilities of each system is conducted to quantify the extent of MUOS improvements. The study finds that MUOS can tolerate a traffic demand rate of about 83 calls/messages per second whereas UFO saturates at roughly 4 calls/messages per second.

MUOS's ability to offer a higher level of quality of service, assured access, and increased capacity will enable more tactical users to share timely information while reducing the uncertainty that they will be able to communicate with their intended recipient. Faster service data rates reduce delays in relaying information during time critical operations. The system represents a paradigm shift in UHF SATCOM from circuit-based, assigned networks to on-demand, global IP-based, net-centric networks. This study has shown that, as specified in its designs, MUOS can provide a level of system performance that will place the system in a preeminent role for the network-centric operations critical to the mission effectiveness of today's military.

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ABSTRACT

The Mobile User Objective System (MUOS) is the DoD's next generation military Ultra High Frequency (UHF) Satellite Communication (SATCOM) system being designed to augment and eventually replace the currently oversubscribed UHF Follow-On (UFO) System. MUOS adapts a commercial third generation (3G) Wideband Code Division Multiple Access (WCDMA) cellular phone network architecture and combines it with geosynchronous satellites (in place of cell towers) with the goal of providing a more capable UHF SATCOM system.

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LIST OF ACRONYMS AND ABBREVIATIONS

3G	Third Generation
BLOS	Beyond Line Of Sight
C4ISR	Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance
CSEL	Combat Survival Evader Locator
DAMA	Demand Assigned Multiple Access
DISN	Defense Information Systems Network
DoD	Department of Defense
DSCS	Defense Satellite Communications System
DSN	Defense Switching Network
EHF	Extremely High Frequency
EMCON	Emission Control
FIFO	First-In-First-Out
FLTSAT	Fleet Satellite
GBS	Global Broadcast Service
IW	Integrated Waveform
JMINI	Joint MILSATCOM Network Integrated
JTF	Joint Task Force
JTRS	Joint Tactical Radio System
kbps	Kilobits Per Second
kHz	Kilohertz
KPP	Key Performance Parameter
LEASAT	Leased Satellite
LES	Lincoln Experimental
MILSATCOM	Military Satellite Communications
MMD	Mean Mission Duration
MUOS	Mobile User Objective System
NCF	Network Control Facility
NCO	Network-Centric Operations
NCS	Network Control Station

NCT	Network Control Terminal
NCTAMS	Naval Computing and Telecommunications Area Master Station
NCTS	Naval Computing and Telecommunications Station
NIPRNET	Non-Secure Internet Protocol Router Network
OCC	On-Orbit-Capability
P2P	Point-To-Point
PMW-146	Navy Communications Satellite Program Office
RAF	Radio Access Facility
SATCOM	Satellite Communications
SCF	Satellite Control Facility
SF	Switching Facility
SHF	Super High Frequency
SIPRNET	Secret Internet Protocol Router Network
SPAWAR	Space and Naval Warfare Systems Command
TACSAT	Tactical Satellite
TDMA	Time Division Multiple Access
UFO	Ultra High Frequency (UHF) Follow-On
UHF	Ultra High Frequency
VHF	Very High Frequency
WCDMA	Wideband Code Division Multiple Access

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I. INTRODUCTION

> Command and Control on-the-move was hampered by the finite number of Ultra High Frequency (UHF) Tactical Satellite (TACSAT) channels available. The demand for UHF TACSAT exceeded the finite capacity and forced continuous prioritization of those available channels as the operations unfolded [1].
>
> Lieutenant General John Abizaid
> U.S. Central Command Senate Confirmation Hearing
> June 24, 2003

A. BACKGROUND

Commercial mobile wireless communication technology is ubiquitous in today's world. Millions of users seamlessly talk and share data with each other on the go throughout the world. The Department of Defense (DoD) is working to achieve a similar capability for the military. The Mobile User Objective System (MUOS) is the DoD's next generation military Ultra High Frequency (UHF) Satellite Communication (SATCOM) system. MUOS is an integrated system that includes an advanced satellite constellation as well as all supporting ground radio access and switching facilities needed to support the worldwide transport of voice and data between a multi-service population of mobile and fixed-site terminal users [2]. According to the Navy Communications Satellite Program Office (PMW-146), the system adapts a commercial third generation (3G) Wideband Code Division Multiple Access (WCDMA) cellular phone network architecture and combines it with geosynchronous satellites (in place of cell towers) with the goal of providing a more capable UHF SATCOM system. The constellation of four operational satellites and ground network control is designed to provide more than ten times the system capacity of the current UHF Follow-On (UFO) constellation, and an improved level of availability and access on demand to satellite communications [3]. MUOS's improved capacity, terminal mobility, and ease of use are expected to deliver secure simultaneous voice and data connections with the usability of a cell phone.

MUOS is being developed to augment and eventually replace the current UFO constellation and provide increased capacity and technology enhancements to support mobile and network-centric communications. The system is required to be able to support ground, naval, and air tactical warfighters who need to operate on-the-move, beyond line of sight (BLOS), in difficult terrain conditions, with small disadvantaged terminals. This military user community is accustomed to a UHF legacy communications system which requires dedicating resources to individual services and networks within pre-assigned frequency ranges. For example, the legacy system reserves a time slot for the exclusive use of a single tactical communications network. This process is inefficient, since most of these networks do not operate on a continuous basis, wasting a large portion of legacy capacity. In contrast, a MUOS end-user can connect to Defense Information Systems Network (DISN) services worldwide, or can directly communicate with any other MUOS end user via either Point-to-Point (P2P) or Group calls, and do so without any intermediate patching or manual routing [3]. MUOS Groups can be joined by dialing a Group phone number and Groups use no system capacity unless a user of the Group is transmitting. Not wasting resources ensures that the maximum number of users will have communications when they need them.

The warfighter community thinks only in terms of prearranged networks, or "nets," with a limited number of users for tactical communications, and this thinking is embodied in current operational plans. Warfighters need assistance in understanding the paradigm shift in UHF satellite communications from legacy (circuit-based, closed networks) to on-demand MUOS (global IP-based, net-centric networks) and applying the enhanced capabilities and advantages of MUOS into their operational environment. Quantifying the level of increase in network performance and quality of service that MUOS provides over the current UFO system will help warfighters gain a better understanding of the new capabilities and potential operational uses.

B. PURPOSE

When stating that MUOS will provide ten times the overall capacity of UFO, PMW-146 uses equivalent 2.4 kilobits per second (kbps) accesses as a common metric

for an apples-to-apples comparison (UFO primarily provides 2.4 kbps voice and data services). While this simple comparison is useful to convey a general message of the increased capability of MUOS over UFO, a more robust and dynamic comparative analysis would be valuable to the military community. This research aims at investigating further the differences between the legacy UFO and MUOS systems in network performance and quality of service. Using modeling of both systems with simulations of relevant operational traffic loads, a comparative study of the performance and capabilities of each system is conducted to highlight their differences and also to gauge the relative improvement for military operations when MUOS enhancements are incorporated.

C. RESEARCH QUESTIONS

1. How does MUOS performance compare to legacy UFO in terms of number of terminals supported, network availability, latency, etc?

2. What enhanced capabilities does MUOS have over UFO? What new services will it provide to its operational users?

3. How will the new capabilities and increased network performance of MUOS transform military tactical communications and future operations?

D. METHODOLOGY

The following methodology is employed to answer the above research questions:

1. Establish the context of UHF SATCOM for military communications.

2. Provide a systems overview of the current UHF SATCOM system, UFO, and its planned successor, MUOS.

3. Create representative models of UFO and MUOS based on each system’s network architecture (elements, connectivity, channels, services, and data flow).

4. Select appropriate levels of traffic load for a Joint Task Force (JTF) operating in a geographical area as demand inputs into simulation runs on the two models.

5. Describe criteria and performance metrics for comparative analysis (number and types of user accesses, data rates, terminals supported, quality of service, utilization).

6. Conduct a comparative analysis using modeling and simulation.

7. Describe the benefit to military operations of any observed enhancements.

E. SCOPE

This performance study focuses on the tactical communication needs of a hypothetical JTF operating in a single large geographic area. Models are created for both UFO and MUOS to simulate the way in which each system would serve the JTF in that area, given each system's own underlying network structure. The intent of this thesis is not to model both systems in their entirety and analyze the total worldwide traffic demand on each, but rather to limit the study to a relevant JTF operational scenario and analyze both systems' capability to support the mission. Scoping the study in this way also allows for the traffic loads imposed on each system to be equal so that a fair comparison can be conducted.

F. BENEFITS OF STUDY

The DoD presents MUOS as a new and more capable UHF SATCOM system with improved capacity, quality of service, ease of use, and availability. The performance investigation conducted in this study will be valuable in quantifying the extent of those improvements and determining both systems' ability to support current and future traffic demands, user needs, and operational requirements. Additionally, a discussion of the new and enhanced communication capabilities of MUOS will provide the necessary assistance to end users in understanding the paradigm shift in the way they communicate. This study will help inform the warfighter of the degree of improvement to the operational communication environment that MUOS can be expected to provide and how that improved environment relates to mission effectiveness. The outcome of this thesis can serve as a guide for military communication planners when they begin to incorporate MUOS into their comprehensive communications plans. It will also inform the warfighter of the practical ways in which MUOS capabilities can be used to enhance operational communications and propel the military through its transformation to network-centric operations (NCO).

II. THE ROLE OF UHF SATCOM

> The UHF portion of the frequency spectrum is of great importance to the military for communications to the mobile warfighter [4].
>
> Jerry Ingerski
> Space and Naval Warfare Systems Command (SPAWAR)
> October 2002

A. MILSATCOM CATEGORIES

Satellite communication has been an integral part of the U.S. military since the 1950s when the first experimental SATCOM programs began and the 1960s when the early operational SATCOM programs demonstrated that reliable communications could be extended to military units equipped with small terminals [5]. Today the U.S. military consistently uses every portion of its allotted share of the frequency spectrum to communicate. Each portion of the radio frequency spectrum has unique advantages and disadvantages. In general, higher frequencies are more directional, carry more information, require more power and the required equipment is heavier, more complex and more expensive. MILSATCOM is used for long-distance, BLOS communications and may be divided into three areas: protected, wideband and narrowband [4]. Figure 1 provides a summary of the current and future MILSATCOM systems.

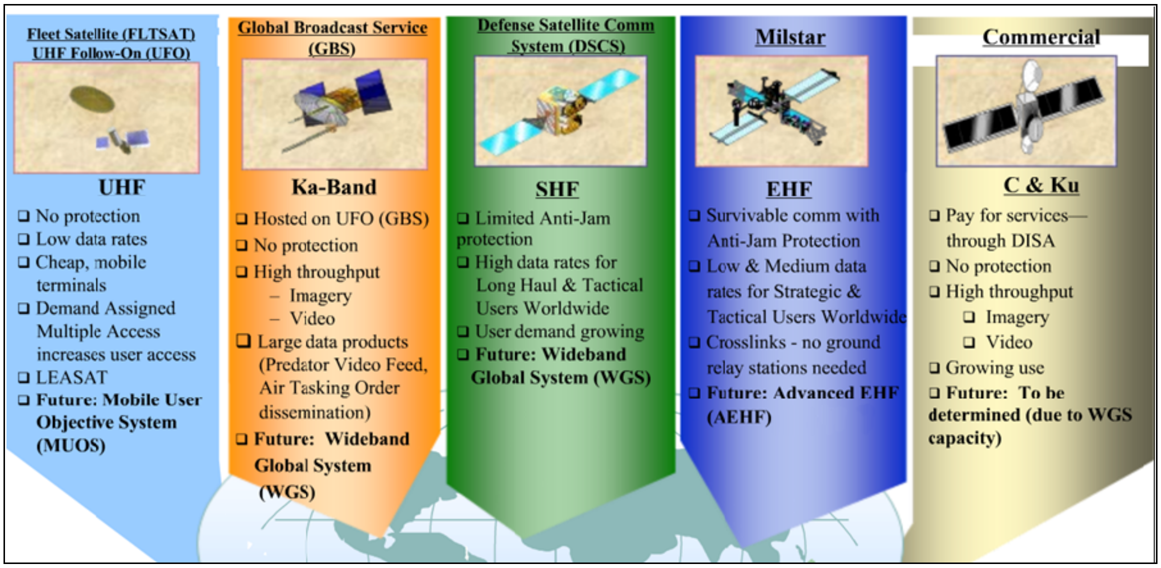

Figure 1. Current and future MILSATCOM systems (After: [6])

1. Protected

Protected systems use the Extremely High Frequency (EHF) payloads contained on the Milstar and UFO constellations. Protected systems are used to avoid jamming, nuclear radiation propagation interference and maintain a stealthy, undetectable signal [4]. Future protected systems include the Advanced Extremely High Frequency System and Advanced Polar System. The DoD’s EHF SATCOM systems offer protected BLOS communications for strategic, tactical, and coalition partner users. These SATCOM systems use onboard partial processing, advanced signal processing, and frequency hopping to provide robust communications that can operate in the presence of interference and within the most challenging environmental constraints. These systems have also been designed to minimize the probability of interception and detection, enabling increased covertness [7].

2. Wideband

Wideband systems emphasize high capacity and use Super High Frequency (SHF) payloads hosted on the Defense Satellite Communications System (DSCS), Global Broadcast Service (GBS) on the last three UFO satellites, or commercial wideband systems [4]. Assured capacity is the primary goal of the military's wideband

communications sector. Wideband data rates are defined as those greater than 64 kbps, although the line between wideband and narrowband is blurring as commercial data rates to disadvantaged users move higher. Wideband systems are used for distributing large volumes of information, such as images or Video Teleconferences. The Wideband Global SATCOM program and the Advanced Wideband System will augment and eventually replace DSCS. These satellites will transmit several gigabits of data per second [8].

3. Narrowband

Narrowband systems use UHF payloads like those contained on UFO and the planned MUOS satellites. Narrowband systems are used for mobile, tactical, urgent and routine voice and data [4]. The DoD’s narrowband SATCOM systems yield lower data rate BLOS communications. In the past, the term "narrowband" implied data rates of less than 64 kbps, but a higher boundary will apply in the future as higher data rates to small terminals become possible [7]. Although the DoD’s UHF SATCOM can be protected by encryption, it is not designed with anti-jam, low probability of intercept, or low probability of detection capabilities [8].

B. UHF SPECTRUM CHARACTERISTICS

1. UHF Advantages

The UHF frequency spectrum has many unique military advantages that have made its use essential to the modern tactical warfighter. The relatively low frequencies and data rates provide terminal hardware advantages including small size, light weight, ruggedness, simplicity, and relatively low cost. Because no other satellite system shares the UHF frequency allocation, non-directional antennas can be used, greatly simplifying mobile communications [2]. These hardware advantages allow terminals suitable for ships, vehicles, aircraft, manpacks and even handheld use. Performance advantages include: signal penetration, worldwide coverage, broadcast networks, and assured access [4]. UHF penetrates heavy weather, jungle foliage and urban environments much more reliably than SHF and EHF frequencies. With a UHF terminal, a warfighter may fight and communicate in all types of weather while using the foliage for concealment.

2. UHF SATCOM Uses

UHF SATCOM is used by all military services and many government agencies mostly for tactical operations involving all facets of Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance (C4ISR). It is the major system for mobile SATCOM, supporting rapid deployments of land, air, and naval forces worldwide. UHF SATCOM provides the warfighter with a wide variety of applications including secure voice, messaging, facsimile, secondary image transfer, packetized data service, and electronic mail [2]. In the beginning stages of an operation, the first attack wave of mobile warfighters primarily use UHF because of the advantages discussed above and there is no time to set up large SHF and EHF communications systems which may require an infrastructure of large antennas, transmission lines, or fiber optic cable. Some of these UHF communications are short-range communications between local forces within line of sight of each other that do not require satellites. However, in order for these early entry forces to communicate further distances or circumvent terrain obstructions, they use UHF SATCOM. In summary, The UHF SATCOM system provides the DoD and other government agencies critical BLOS communications for tactical and special operations. UHF SATCOM is currently the only military system that enables users to conduct communications on-the-move and under all weather conditions and cover.

C. HISTORY OF UHF SATCOM

UHF SATCOM was developed by the U.S. Navy and has been providing service to mobile users throughout the DoD and other government agencies for more than thirty years. Over these years, the Navy has been employing different generations of UHF satellites — Lincoln Experimental (LES), Marisat Gapfiller, Fleet Satellite (FLTSAT), Leased Satellite (LEASAT) Gapfiller, and UFO (Figure 2) [2].

Figure 2. Artist rendition of UFO satellite (From: [9])

Table 1 provides a summary of the status of UHF SATCOM satellites. The highlighted satellites have previously experienced their end of life. The UFO F1 satellite suffered a launch vehicle failure.

UFO	Launched	Age (yrs)
F2	Sep-93	17.8
F3	Jun-94	(11) Jun-05
F4	Jan-95	16.4
F5	May-95	16.1
F6	Oct-95	15.6
F7	Jul-96	14.9
F8	Mar-98	13.2
F9	Oct-98	(7.9) Sep-06
F10	Nov-99	11.6
F11	Dec-03	7.5
FLTSAT		
F7	Dec-86	24.5
F8	Sep-89	21.6
LEASAT		
F5	Jan-90	21.4

Table 1. Status of UHF SATCOM satellites (After: [10])

MUOS is the next DoD UHF SATCOM system and is being developed to provide the warfighter with modern worldwide mobile communication services. However, because of delays in MUOS development, the first launch is now expected in May 2012, 26 months later than originally planned [11]. Figure 3 provides a depiction of a MUOS satellite.

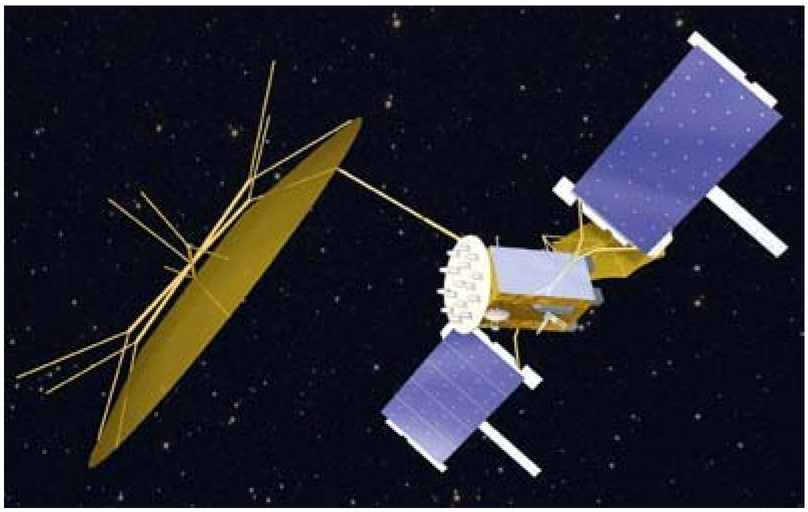

Figure 3. Artist rendition of MUOS satellite (From: [12])

D. CAPACITY PROBLEM

Great demand exists for the use of the UHF portion of the spectrum because of all the operational advantages that it provides to the mobile warfighter. This demand has led to the proliferation of UHF terminals onboard practically every type of military platform from aircraft, submarines, and warships to tanks, trucks, cruise missiles, and manpacks. Handheld terminals supporting UHF MILSATCOM are currently limited to radios issued through the Combat Survival Evader Locator (CSEL) program [13]. In emergency situations, the UHF SATCOM mode can support two-way secure data communications between a base station and the survival radio over a dedicated channel. Overall, the number of UHF SATCOM terminals has grown substantially, and there are plans for increased numbers in the future. The current UFO system capacity does not meet current demands, much less the increased demands of the future. The UFO system and its predecessors have been consistently oversubscribed. The main problem with UHF

SATCOM is that there it just does not enough of it. There are many more potential users of UHF SATCOM than there are available channels [14]. It is often claimed that the biggest failing of the legacy UFO system is that it has insufficient capacity to provide service to a large percentage of its potential users [15]. The UHF capacity problem is such that the U.S. military's own operational manual, *Multi-service Tactics, Techniques, and Procedures for Ultra High Frequency Tactical Satellite and Demand Assigned Multiple Access (DAMA) Operations* warns, "UHF TACSAT bandwidth is an extremely scarce resource" [16]. The DoD's acquisition force has responded by requiring that the next generation MUOS provide a considerable increase in capacity over the current UFO system. According to a SPAWAR Acquisition Panel brief, capacity is, in fact, the warfighter's number one Key Performance Parameter (KPP) for MUOS [6].

As work on the future MUOS system continues, the UFO system is on station providing continuous support to the warfighter. The first UFO satellite was launched in 1993, and the final satellite was launched in 2003. The satellites were developed with a design life of fourteen years and a mean mission duration (MMD) of ten years [10]. For on-orbit space systems, the MMD is the average time the system is operational before a mission critical failure occurs, i.e., the duration it is expected to remain satisfactorily operational. FLTSAT and LEASAT each have a design life of only five years [10]. As the current UFO constellation of eight satellites reaches its end of life, the time gap prior to the first MUOS launch combined with greater than expected demand for UHF SATCOM capability has created a potential decline in availability of legacy capacity [17]. Figure 4 displays a graph of the predicted availability of the eight UFO satellites over time as a result of a probabilistic analysis conducted by PMW-146 in August 2010.

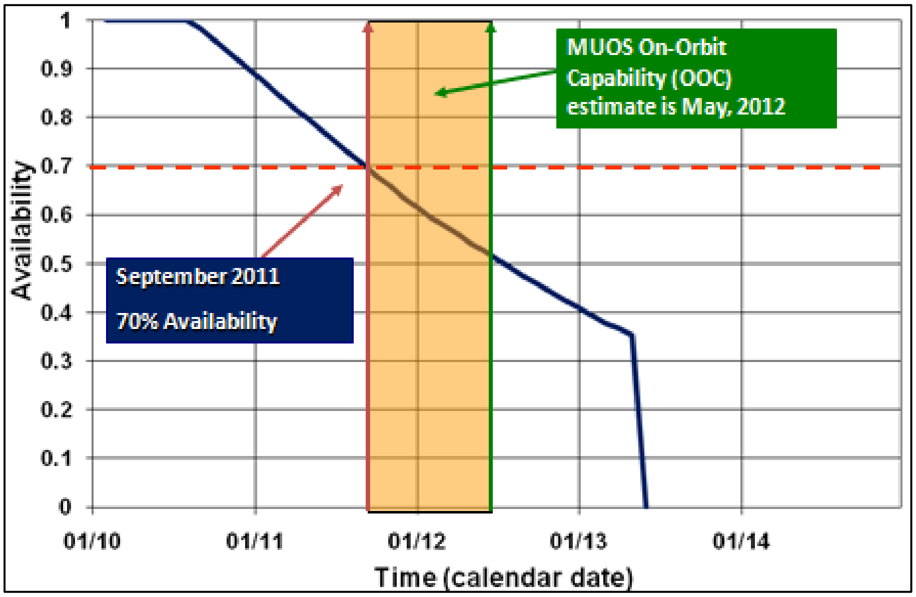

Figure 4. UFO projected availability (After: [10])

The Navy is required to maintain a 70 percent likelihood of UHF capacity availability equivalent to eight fully functional satellites. The shaded area on the graph represents a nine-month gap between projected availability and MUOS On-Orbit Capability (OOC). The failure of any UFO satellite or critical component would drastically change this projected availability. Furthermore, much of the rapid growth in demand for bandwidth, which is exacerbating the capacity problem, can be attributed to the DoD's increasing emphasis on information superiority and the continued drive to transition the force towards network-centric operations (NCO).

E. NETWORK-CENTRIC OPERATIONS

Today's Information Age is one of rapid technological change and continually increasing computing power which allows the free flow of information through swift global communications and networking. For the DoD, information dominance through information technology is becoming an integral part of the fulfillment of its daily operations and missions. The concept of NCO represents the military's response to the Information Age. The term NCO broadly describes the combination of strategies, emerging tactics, techniques, and procedures, and organizations that a fully or even a partially networked force can employ to create a decisive warfighting advantage [18].

NCO as a source of warfighting advantage follows from the following line of reasoning:

- A robustly networked force improves information sharing.
- Information sharing enhances the quality of information and shared situational awareness.
- Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
- These, in turn, dramatically increase mission effectiveness [19].

In 2003, General James Cartwright, then Commander, U.S. Strategic Command, captured the way in which NCO can provide advantages to military forces by explaining, "NCO is an information superiority-enabled concept of operations that generates increased combat power through the empowerment of the different types of users by virtue of their connection to and participation in the network. It leverages an information-rich environment to impart a high degree of self-synchronization by networking sensors, analysts, decision makers, and operators into effective chains to achieve shared awareness, increased speed of command, and unity of effort. This in turn yields higher tempos of operation, the ability to react to the unexpected, greater mission effectiveness, and increased lethality and survivability" [20].

As U.S. military forces continue to downsize, fewer — and therefore more dispersed and mobile — warfighting and support elements have acquired an increased dependence on timely information to remain effective and dominant in the battlespace. The purpose of NCO is to enable the rapid acquisition of that critical information through the networking and data-sharing between those geographically dispersed forces. In this way, NCO enable military forces to translate an information advantage into a battlefield advantage. This continued evolution of the military's NCO strategy is resulting in the increased reliance on the availability of communication links, especially the TACSAT channels that allow dispersed mobile forces to stay connected and share the information they rely on. Clearly, MUOS will play a role in the DoD's emerging NCO vision because it is a system designed to provide the interoperable, robust, network-centric

communications needed by the mobile warfighter for future operations. MUOS is expected to significantly increase the current UFO capability for mobile forces to stay connected, communicate, and share information no matter the weather, their geographical location, or environment. One of the goals of this thesis is to quantitatively measure the level of increase in communications capabilities that MUOS will provide over UFO and to determine the degree to which MUOS will contribute to NCO.

III. UFO AND MUOS SYSTEM OVERVIEWS

A. INTRODUCTION

This chapter presents a systems overview of both the UFO and MUOS UHF SATCOM systems. The overviews include descriptions of the network architectures, communication services provided, and technology and processes used in the operation of each system.

B. UHF FOLLOW-ON

1. UFO Satellite Constellation

The Navy is responsible for providing narrowband satellite capacity to U.S. military forces around the world. The UHF spectrum allocated for narrowband military satellite communications (MILSATCOM) is located at the boundary between the Very High Frequency (VHF) and UHF frequency bands. Each UFO satellite is outfitted with multiple transponders. The transponder receives an uplinked signal at a given frequency, amplifies it, and then converts it to another frequency for rebroadcast as downlink. Uplink frequencies are located at the lower end of the UHF band (292 to 317 MHz) while downlink frequencies are located at the upper end of the VHF band (243 to 270 MHz) [14]. UHF MILSATCOM is primarily provided by the UFO satellite constellation. Eleven UFO satellites have been launched from 1993 through 2003 as "follow-on" to the LEASAT and FLTSAT UHF satellites. Today, the service depends on eight UFO satellites which are currently remaining and supplying UHF MILSATCOM along with the remaining FLTSAT and LEASAT satellites. The eight UFO satellites are approximately 23,500 miles above the earth in geosynchronous orbit about the equator, with two satellites in each of four overlapping geographic footprint areas centered over the Continental United States, the Pacific Ocean, the Atlantic Ocean, and the Indian Ocean to provide worldwide coverage [14]. UFO satellite locations and coverage areas are shown in Figure 5.

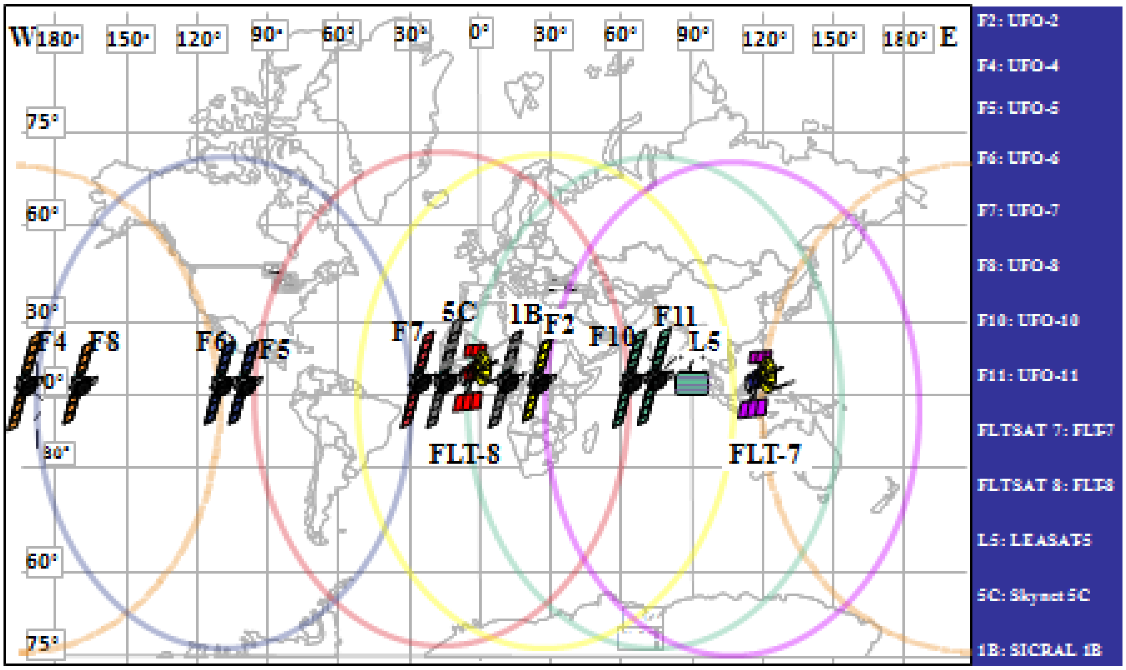

Figure 5. Current UHF SATCOM coverage (From: [10])

A single UFO satellite supports 38 UHF communication channels, comprised of 17 25-kHz UHF communication channels and 21 5-kHz channels. Each UHF channel uses an independent transponder operating as a bent pipe for uplink and downlink. Technically, a co-located satellite pair operating together provides a total of 78 channels for use within each coverage area. Of these 78 channels, there are 42 5-kHz channels, 34 25-kHz channels, and two 25-kHz fleet broadcast downlinks that are fed by jam-resistant SHF and EHF uplinks (not applicable for this thesis).

2. Evolution of UHF DAMA

The first and still occasional use of UHF MILSATCOM channels is in the dedicated access mode (also called single access mode) where the entire channel bandwidth is dedicated to a single communications requirement, regardless of the actual bandwidth required. Each such communications requirement is also referred to as a user service, or as a network (or net), because it typically involves a network of users that exchange data with one another either in a push-to-talk mode or by using higher-layer protocols. With channels operating in the single access mode, there is a simple one-to-

one correspondence between the number of UHF MILSATCOM channels available and the number of communications requirements or networks that can be supported at any given time. Under the dedicated access scheme, all terminals in a net operate on one uplink radio frequency paired with one downlink frequency and assigned exclusively to the net. A net's associated uplink frequency paired with its downlink frequency constitutes a *single* channel dedicated for the net's operational use during an assigned span of hours or days. All stations in the net monitor its channel for calls. Each station has a unique station identifier that is used to identify it to other station operators in the net. Usually, one station in the net is designated as the network control station (NCS) to supervise and authenticate the entry and exit of authorized stations [16]. The channel is always occupied by that net, so that even if no terminals on the net have anything to transmit (dead time), the channel is unavailable for other use.

DAMA standards were introduced in an attempt to make more efficient use of the limited UHF MILSATCOM resources. DAMA provides multiple access to a UHF channel through the use of time division multiple access (TDMA), and allows such accesses to be demand assigned [21]. Thus, DAMA is a channel access scheme composed of demand assigned TDMA. TDMA is a multiple-access technique in which many users share the same channel on a time division basis. Users burst their traffic in a periodic time frame (time slot), and for the duration of their burst, they have dedicated access to the transponder. Demand assigned refers to the dynamic assignment of channel resources based on user demand. Service is temporarily assigned and when the service is no longer needed the user relinquishes the resource to the control authority for reassignment [22]. TDMA is accomplished when controller hardware at a NCS transmits control signals that establish precisely recurring intervals of time (frames). A frame is typically one or more seconds in duration. Each frame is subdivided (time division) into precise time slots. Certain slots in each frame are reserved for the controller station to receive user station service requests, or to transmit control signals via the satellite. Other time slots are available for user stations to transmit signal bursts to each other via the satellite. User nets are assigned slots within the frames on a given channel [16].

3. DAMA Military Standards

UHF DAMA has two variants with different communications services and operating schemes, the 5-kHz and the 25-kHz DAMA waveforms, which are defined respectively in the MIL-STD-188-182 series and MIL-STD-188-183 series. The 5-kHz DAMA protocol primarily supports multiple-user 75 bits per second (bps) to 2.4 kbps secure data that can tolerate delays induced by the waveform, with voice being secondary [16]. It can provide effective resource sharing for voice and data communications. However, the delays associated with the use of 5-kHz DAMA make it difficult to use for conversational voice communications. A 5-kHz channel can support only one 2.4 kbps time slot. The 25-kHz DAMA protocol supports equipment selective data rates of 75 bps to 16 kbps for data and secure voice. It has shorter frame times and supports more data rates and simultaneous users than does 5-kHz DAMA. A 25-kHz DAMA channel can support a maximum of five 2.4 kbps voice/data network time slots. Time slots supporting data rates between 75 bps and 1.2 kbps are impractical for most users and seldom used [23].

In the 1996 instruction CJCSI 6251.01, the Joint Chiefs of Staff mandated that all users of UHF MILSATCOM are required to have DAMA terminals that are interoperable with the prescribed DAMA military standards. Since then, the drive to DAMA-only usage has been long and arduous. The 2009 updated version of the instruction still includes a waiver process for user terminals that cannot meet the DAMA standards [23].

Although not widely adopted yet, a revised set of DAMA military standards (MIL-STD-188-181B, MIL-STD-188-182B, MIL-STD-188-183B) known as the integrated waveform (IW) have been designed to improve the UFO system by fixing deficiencies identified with the previous standards, increasing the number of potential accesses, and increasing throughput. The IW standards will more than double the channels over the previous DAMA standards. A 25-kHz channel running IW can support on the average twelve 2.4 kbps time slots compared to only five for a 25-kHz channel running with the previous standards. The IW will achieve similar throughput improvements on 5-kHz channels. The long TDMA frame of the previous 5-kHz DAMA

waveform which induces substantial delays for the user is replaced with the shorter MIL-STD-188-183 TDMA frame structure used on the 25-kHz channels which avoids those delays [24].

4. DAMA Network Architecture

Initially, different controller hardware was developed for controlling 5-kHz and 25-kHz channels. The Joint MILSATCOM Network Integrated (JMINI) control system provides integrated network control terminals (NCT) that centrally handle all 5-kHz/25-kHz DAMA and non-DAMA channels on UFO satellites in each footprint. Three Naval Computer and Telecommunications Area Master Stations (NCTAMS) and one Naval Computing and Telecommunications Station (NCTS) house JMINI control system hardware and software suites. These stations are located in two adjacent satellite coverage areas with the ability to control satellite channels in two satellite coverage areas, providing redundant control capability for each coverage area [14]. Table 2 provides a summary of NCTAMS locations and primary control responsibilities.

DAMA Primary Channel Controller	NCTAMS Location	Satellite Footprint
NCTAMS LANT	Norfolk, VA	Continental U.S.
NCTAMS EURCENT	Naples, Italy	Atlantic Ocean
NCTAMS PAC	Wahiawa, HI	Pacific Ocean
NCTS Guam	Finegayan, Guam	Indian Ocean

Table 2. DAMA primary channel controllers

For a simple DAMA architecture with a single satellite footprint covering all users with the resource controller in an NCT, Figure 6 illustrates the sequence of transmissions involved in setting up and starting a DAMA call from user A to user B.

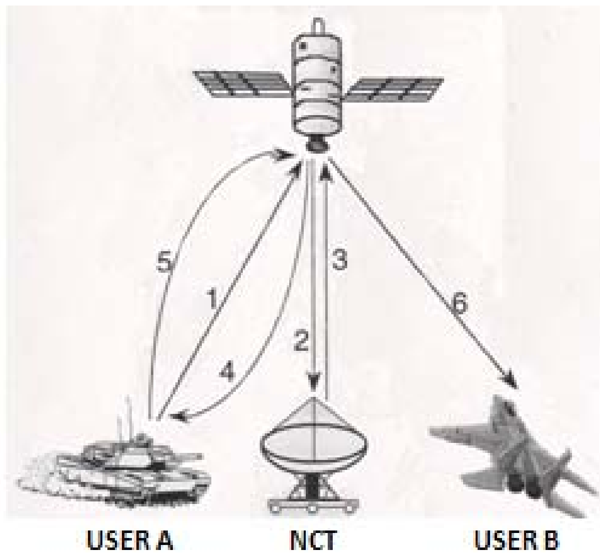

Figure 6. Sequence of transmissions between users and NCT (From: [25])

Hops 1-2 transmit the request from user A to the NCT. If access to a time slot on the channel is available, the NCT sends the channel assignment to user A (hops 3-4). User A then begins transmitting to user B (hops 5-6). Note that this architecture imposes a minimum of two earth-satellite round trip propagation delays (more if there are collisions) until user A is granted access to the channel and can begin transmitting data [25]. Propagation delay is the length of time it takes for a signal to reach its destination. Delays inherent in the framing of DAMA waveforms and processing in the NCT add to this total overhead delay in requesting and receiving access. Another round trip propagation delay will be incurred in the actual data transmission from user A to user B.

C. MUOS

MUOS is an integrated system that includes a satellite constellation as well as all supporting ground systems including radio access facilities (RAF), switching facilities (SF), network control facilities (NCF), and satellite control facilities (SCF). The MUOS program started in 2002, and the Navy's Communications Satellite Program Office (PMW 146) is responsible for overseeing its development. Lockheed Martin is the prime system contractor and satellite designer for MUOS. Full system capability is estimated for 2015.

1. MUOS Network Architecture

MUOS departs completely from operation over individual 5-kHz and 25-kHz bandwidth UHF transponders. The system actually modifies a commercial 3G WCDMA cellular phone architecture by using military satellites in place of terrestrial cell towers. MUOS is being designed to provide global coverage from a geosynchronous orbit via a four satellite constellation, one in each of the four geographic footprint areas covered by the current UFO constellation. The constellation will also include one in-orbit spare. Figure 7 displays MUOS satellite coverage areas. Each satellite is displayed over its respective coverage area and labeled accordingly as Pacific (PAC), Continental U.S. (CONUS), Atlantic (LANT), and Indian Ocean (I.O.).

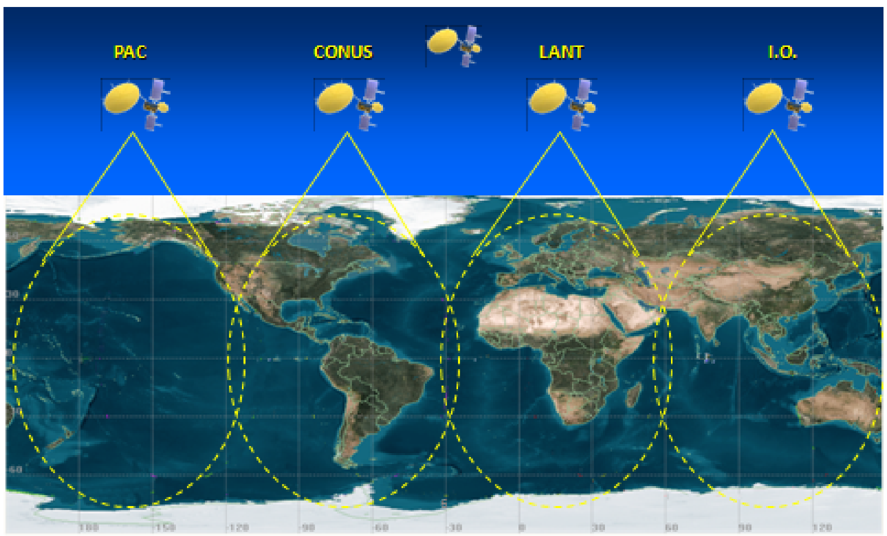

Figure 7. MUOS satellite coverage areas (After: [26])

Coverage from each satellite is achieved via 16 fixed overlapping spot beams generated by the satellite's receive/transmit multi-beam antenna. Each beam supports four 5-MHz UHF WCDMA radio frequency carriers providing a total of 64 WCDMA carriers available per MUOS satellite. Figure 8 contains a representation of the satellite spot beams. The large dashed circles represent each satellite's footprint, and the smaller overlapping circles within each of the larger circles represent the spot beams.

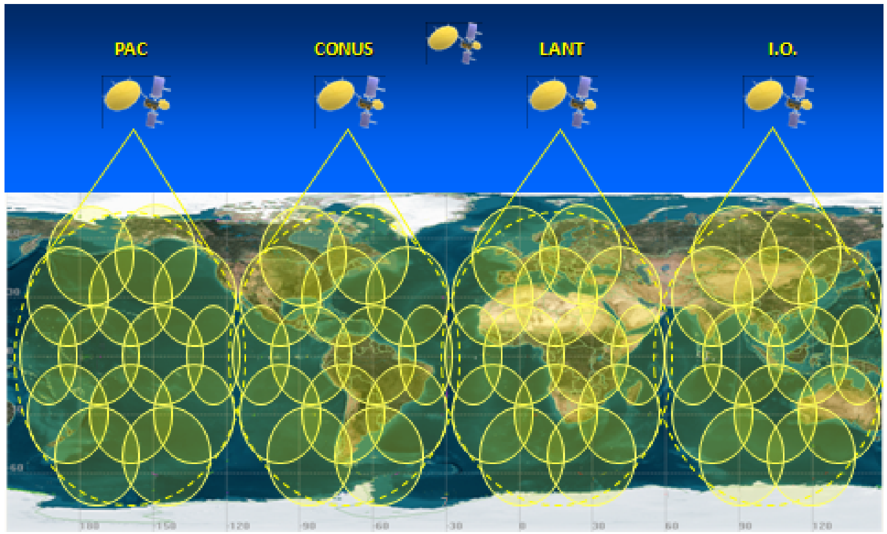

Figure 8. MUOS overlapping spot beams (After: [26])

In addition to the satellite constellation, the MUOS system includes a terrestrial network, comprised of four ground sites (Hawaii, Norfolk, Sicily, and Australia) and two switching/network management facilities (Hawaii and Norfolk). Figure 9 shows the geographical locations of the ground stations. The two switching facilities in Hawaii and Norfolk each have connections with the Defense Switching Network (DSN) and the Defense Information Systems Network (DISN) providing the system with robust DSN telephone service and access to the Non-secure Internet Protocol Router Network (NIPRNET) and Secret Internet Protocol Router Network (SIPRNET).

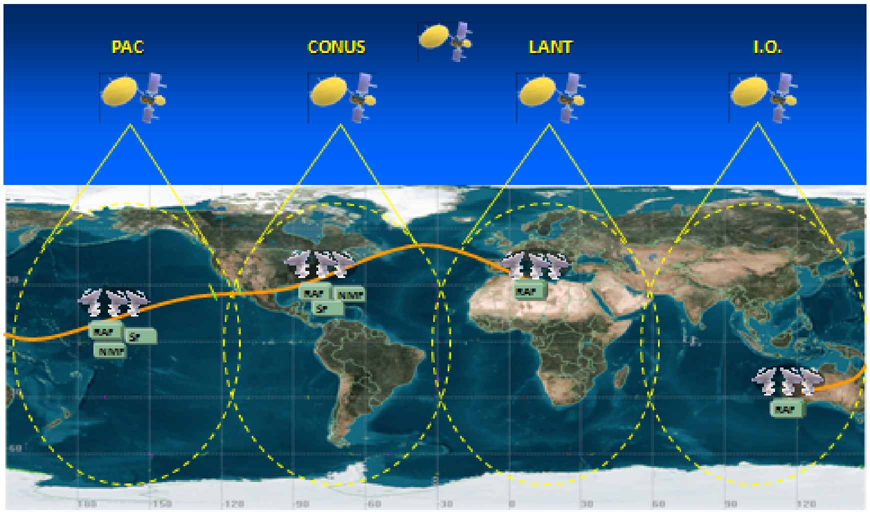

Figure 9. MUOS ground station locations: (After: [26])

MUOS ground stations (Figure 10) are interconnected by a terrestrial networking infrastructure, enabling any two MUOS users to communicate regardless of their location [15]. Legacy UHF SATCOM users are limited to communicating within their own satellite coverage area unless a complex relaying process consisting of multiple satellite hops is performed by the NCTAMS.

Figure 10. MUOS ground station (From: [27])

2. MUOS Data Flow

Data transmitted between MUOS users will travel much differently in the MUOS network as compared to the legacy network. A UFO satellite acts as a bent pipe for users in its satellite coverage area who communicate directly with each other by means of UHF signals. These direct communications can be immediate if using dedicated access mode or incur some delay as a result of the time required to request and receive access from a NCT if using DAMA mode. In either mode, all signals are UHF. The MUOS satellite operates as a bent pipe between a user and a ground RAF. The satellite communicates with its users over UHF and with the RAF over Ka-Band. Figure 11 illustrates the path of user A operating in one satellite footprint transmitting to user B operating in another satellite footprint.

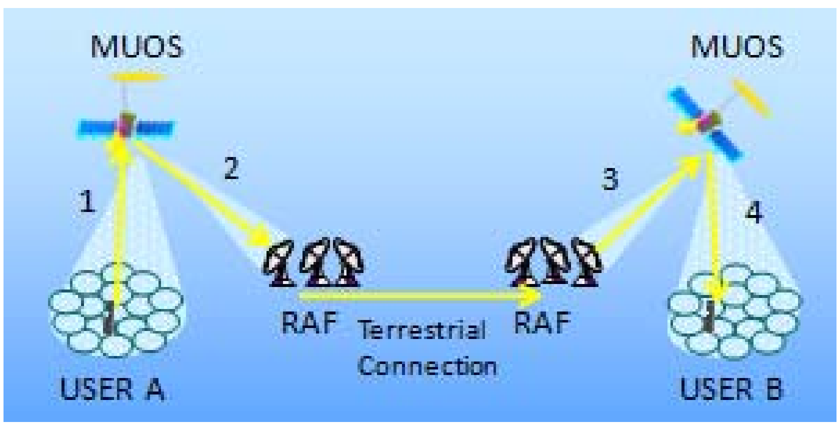

Figure 11. Transmission between users under two different satellites (After: [28])

Data from user A is transmitted to the satellite overhead via UHF WCDMA uplink in path 1. The satellite sends the data to the RAF via Ka-Band downlink in path 2. The RAFs are connected through a fiber optic terrestrial network infrastructure. Since the information is destined for a terminal outside of the local footprint, the ground RAF forwards the information to one of the switching facilities, which routes it to the appropriate RAF. The receiving RAF transmits the data to the second satellite via Ka-Band uplink in path 3. Finally, the second satellite sends the data to user B via UHF WCDMA downlink in path 4 [29]. In this architecture, data transmission requires two

earth-satellite round trip propagation delays. Figure 12 illustrates a similar transmission; this time from users operating in the same satellite footprint.

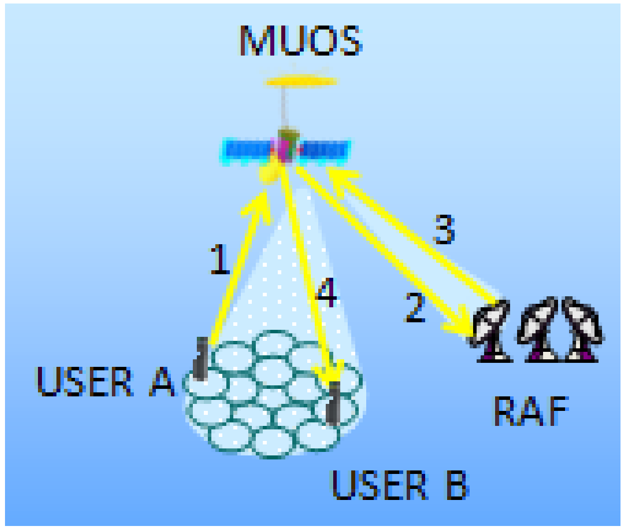

Figure 12. Transmission between users under the same satellite (After: [28])

Data from user A is transmitted to the satellite via UHF WCDMA uplink in path 1. The satellite sends the data to the RAF via Ka-Band downlink in path 2. Since the information is destined for a terminal within the local footprint, the ground RAF transmits the data back to the satellite via Ka-Band uplink in path 3. Finally, the second satellite sends the data to user B via UHF WCDMA downlink in path 4. This transmission scenario also requires two earth-satellite round trip propagation delays. In this way, MUOS network architecture is such that every transmission between users requires two earth-satellite round trip propagation delays (one for up UHF, down Ka-Band and one for up Ka-Band, down UHF) whether the users are on opposite sides of the world or standing right next to each other. While this type of architecture seems to add unnecessary propagation delay, it is a result of replicating the cellular phone structure of commercial wireless technology. Besides, the MUOS satellite would require increased processing power and further design to attempt to fulfill the function of the switching facility by determining if the intended transmission was within its own footprint and could just be converted to UHF downlink [29].

3. WCDMA Waveform

Traditional UHF SATCOM systems evolved from individual UHF channels allocated to users, to channels time shared between multiple users because demand outstripped supply for available bandwidth. Channels dedicated to a single user or group of users did not allow the efficient sharing of the resource (bandwidth). Time-sharing of the bandwidth through TDMA improves the efficiency of channels under high demand, but requires a centralized control function to maintain the time slot synchronization between all system users (e.g., the JMINI controller). While TDMA improves resource efficiency, it cannot determine the dead time, i.e., whether any user on the system is actually using his portion of the resource (bandwidth in his time slot). A TDMA controller will share the bandwidth across as many time slots as the system supports even if the users are silent, effectively blocking out users who are waiting for access. DAMA was developed to help solve this problem by allowing unused channels to be reallocated, albeit slowly.

The next progression is a system that doles out bandwidth based on actual instantaneous need. Such a system must dynamically measure bandwidth actually being used or requested by users on the system and allow more users to access the system if bandwidth is available. This is what the WCDMA waveform employed in commercial 3G mobile telecommunications networks does. By allowing every user wishing to access the system to do so (at absolute minimum bandwidth), each user can request to create a connection to another user or network at any time (the same way that a cellular phone user is always on the net and can place a call) [29]. Figure 13 provides a visual comparison of TDMA and WCDMA.

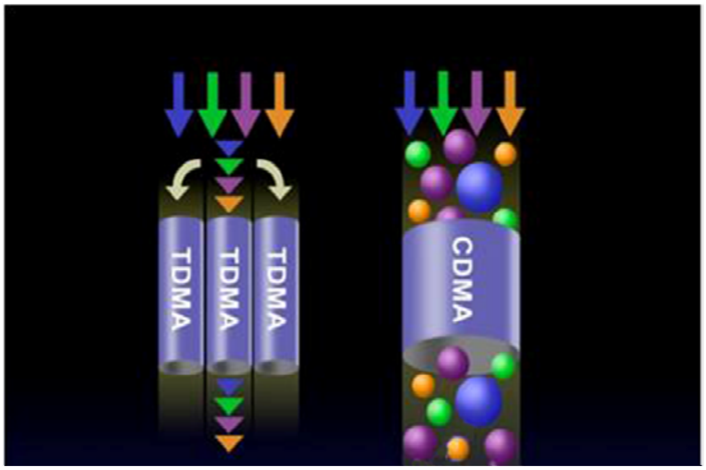

Figure 13. TDMA/WCDMA comparison (After: [10])

With WCDMA technology, terminals are issued unique channelization spreading codes that spread the signal sent by a user over the maximum bandwidth of the system allowing multiple users to operate simultaneously within the same spectrum. MUOS allocates channelization codes in various combinations to support different data rates and types of service. Higher data rate services consume more codes than lower data rate services. Each WCDMA carrier (4 per beam) has 512 channelization codes with approximately 494 available for user communications [29]. Table 3 lists the number of codes required for various data rate services.

	Service			
	64 Kbps	32 Kbps	9.6 Kbps	2.4 Kbps
Number of Codes Required	16	8	2	1

Table 3. Channelization codes for data rates (After: [29])

4. MUOS Services

MUOS supports the transfer of voice and data information through MUOS compatible terminals via several types of service at a range of data rates.

a. MUOS Terminals

While the MUOS program is responsible for the development of the system's WCDMA waveform, the Joint Tactical Radio System (JTRS) program is

responsible for the development of a wide variety of MUOS compatible terminals [15]. The realization of these terminals will provide a leap forward in mobile SATCOM capability. A summary of various terminals and their associated data rates is presented in Table 4.

Terminal Configuration	User/Platform	Data Rate (kbps) By Environment Optimum	Highly Stressed	Terminal Speed (Maximum) (mph)
Aircraft	Large Aircraft	64	32	900+
Aircraft	Fighter/Attack	16	16	900+
Aircraft	Helicopter	16	16	220
Aircraft	UAV	64	64	460
Aircraft	Missile	32	32	667
Handheld	Soldier	32	9.6	6
Handheld	Vehicle	64	32	65
Manpack	Soldier	64	64	0
Manpack	Vehicle	64	64	0
Manpack	Vehicle	64	32	65
Manpack	Advanced Amphibious Assault Vehicle (AAAV)	64	32	45
Sensor	Remote Sensor	2.4	2.4	0
Ship	Large/Small Deck	64	64	30+
Submarine	SSN/SSBN	64	32	25+
Boat	Pursuit Boat	2.4	2.4	60+

Table 4. MUOS terminals and data rates (From: [10])

b. Group Communications

Group communications in MUOS are equivalent to the "netted" communications in the legacy UHF SATCOM system. This service is half-duplex with one transmitter and multiple listeners. All groups must be preplanned, but planners also have the ability to establish provisions in their plans for ad hoc groups that can be created and joined on the battlefield. Group voice services include conversational voice at 2.4 kbps and voice recognition at 9.6 kbps. Group data services include data rates from 2.4 kbps to 64 kbps.

c. *Point-to-Point Communications*

Point-to-Point (P2P) communications consist of full-duplex communication where one terminal communicates with one other terminal. P2P supports voice and data communications (2.4 kbps to 64 kbps). In a P2P call, a MUOS terminal can either communicate with another MUOS terminal, with a DSN or regular telephone, or connect to the NIPRNET/SIPRNET. For a voice session, the call is initiated by the originating user dialing the MUOS phone number of the terminating user [29].

d. *Additional Features*

MUOS supports broadcasts from specifically designated MUOS user terminals to designated MUOS user terminals over a defined geographic region. Additionally, functionality for emission control (EMCON) operations, where users can operate their terminals in a receive-only, non-emission mode, is also included if the user needs to avoid electronic detection [29].

e. *Legacy Support*

Each MUOS satellite also carries a legacy payload similar to that flown on the currently deployed UFO F11 satellite to extend the useful life of the legacy system and allow for a gradual transition to the MUOS WCDMA waveform [29].

D. CAPACITY COMPARISON

The number of simultaneous 2.4 kbps voice accesses is often used as a common metric to compare MUOS with UFO. In a single geographic coverage area, two co-located UFO satellites can support 212 voice nets. The number of voice nets follows from 42 5-kHz channels (capable of providing a single 2.4 kbps access) and 34 25-kHz channels (capable of providing five 2.4 kbps accesses). A total bandwidth capacity of 508.8 kbps would then follow from the 212 simultaneous accesses at 2.4 kbps. PMW-146 reports that MUOS will be capable of providing 4,083 simultaneous accesses from the MUOS payload and 106 from the legacy payload for a total of 4,189 [10]. This would represent a total bandwidth capacity of 10.05 Mbps per MUOS satellite resulting from the 4,189 simultaneous accesses at 2.4 kbps.

The 4,083 accesses reported may, at first, appear to be lower than expected. Considering that each MUOS satellite has 64 WCDMA carriers, each carrier has 494 channelization codes, and one 2.4 kbps access requires a single code, one would expect the number of 2.4 kbps accesses to be 31,616. However, this theoretical code limit assumes that every code on all 64 carriers can be used at once. This is not the case because of satellite power and multiple access interference. Satellite power would run out long before all 494 codes could be loaded onto all 64 carriers.

IV. SIMULATIVE STUDY

A. INTRODUCTION

Simulation is the process of designing a model of a system and carrying out experiments on it as it progresses through time in order to understand the behavior of the system, examine its performance characteristics, and evaluate various strategies for the operation of the system. A model is an approximation, representation, or idealization of selected aspects of the structure, behavior, operation, or other characteristics of a real-world process, concept, or system, i.e., an abstraction [30]. Modeling and simulation has become an important tool for systems engineers to employ in all phases of the acquisition and systems engineering process. This study uses modeling and simulation to conduct a comparative analysis of the network and communication performance of the MUOS and legacy UFO systems. The goal of the performance investigation is to provide insight into both systems' ability to support current and future traffic demands, user needs, and operational requirements.

B. OPERATIONAL SCENARIO

In this notional scenario, U.S. defense leadership has established a Joint Task Force (JTF) to respond to hostile aggression by a rogue state against a U.S. ally. The JTF is to be deployed to the area to display a show of force in support of its ally and respond to the hostile actions of the aggressor. The JTF composition includes:

- 1 Navy Carrier Strike Group
  - 1 Aircraft Carrier
  - 1 Carrier Air Wing
  - 1 Aegis Cruiser
  - 3 Aegis Destroyers
  - 1 Supply Ship
- 2 Navy SEAL Teams
- Air Force Assets
  - 1 KC-130
  - 1 E-3
  - 1 E-8C
- 1 Army Brigade Combat Team
  - 3000-3500 troops

- Several hundred medium-armored vehicles, humvees, and trucks of various configurations

The JTF rapidly deploys to the theatre of operations with naval forces on station and army and air forces conducting operations from a local military base inside the allied country. As with any major military operation, communications within the JTF are vital to mission success. A sufficient number of robust lines of communication are needed to support intelligence gathering and dissemination, command and control, and domain situational awareness for the forces of the JTF as they conduct their mission.

C. MODEL DEVELOPMENT

This simulative performance study uses Extend™ discrete event simulation software to model the MUOS and UFO systems as they would be applied to support the tactical communications traffic demands of a JTF with dispersed forces in air, sea, and mountainous terrain and urban areas of its large geographic area of operation. The two models are created based on the network architecture, data flow structure, and resource limitations of the systems as described in Chapter III. The study assumes that all operations and communication requirements fall within one spot beam of a MUOS coverage area (resultantly, all communications would also fall under one UFO coverage area). All users, both transmitting and receiving, are within this same location. This assumption also allows for equal traffic demands to be applied to each system model. Moreover, the majority of communications in such a scenario are between users within the geographic area in which the JTF would be operating.

1. UFO Model

The JTF requires significant communications resources to operate and perform its important mission. This study assumes that 40 of the 76 available UHF SATCOM communication channels provided by a co-located pair of UFO satellites in their entire coverage region are dedicated to the JTF commander. This allocation includes 20 5-kHz channels and 20 25-kHz channels with all channels being in DAMA mode under MIL-STD-182A and MIL-STD-183A for a best case UFO capability.

Because the 5-kHz and 25-kHz channels function differently and have different capacity for supporting service accesses, the UFO model requires separate element characteristics for each channel type.

a. 5-kHz Channel Model Element

Recall that a 5-kHz UFO channel can support one 2.4 kbps access and that the channel, because of delays associated with the relatively long frames of the 5-kHz waveform structure, is primarily used for data. The 5-kHz model element of this simulation is therefore subjected to primarily data communications requests. All terminals are assumed to have already been configured for use on the channel by the terminal operators. Users are assigned to their respective 5-kHz channel and request access to the 2.4 kbps data service to transmit data to other users on the channel.

Several delay components contribute to the total delay of a data message, which is the duration between the time at which the sender requests access to transmit and the time at which the data is completely received by the recipient on the other end. These delays include the link set-up overhead delay, service queue delay, and the actual data transmission delay. The link set-up delay is the delay resulting from the request/receive access process between the user and the NCT. As discussed in Chapter III, the link set-up delay has a fixed delay component associated with the number of earth-satellite round-trip propagation delays. For a UHF wireless signal traveling at the speed of light to a geosynchronous satellite 23,500 miles away, one round trip propagation delay equals approximately 0.25 seconds. The inter-workings of the DAMA waveform framing and the processing in the NCT are beyond the scope of this thesis; however, previous research has shown that the link set-up delay for 5-kHz DAMA is on average 4 seconds [31]. This 5-kHz channel model element accounts for the link set-up overhead delay by adding 0.5 seconds (two round trip propagation delays) and a delay value based on an exponential distribution with a mean of 3.5 seconds to every message transmitted over the 5-kHz channel. Separately, the data transmission delay is a function of the data rate service provided by the channel and the size of the data message. The 5-kHz channel model element is constructed to allow for one 2.4 kbps service access at a

time on the channel, as per the system description in Chapter III. A data message must be transmitted by the sender over the channel and then downloaded by the receiver before the 2.4 kbps access is relinquished. Terminals on the channel only communicate with terminals also on the channel. Figure 14 presents a diagram of the element model structure.

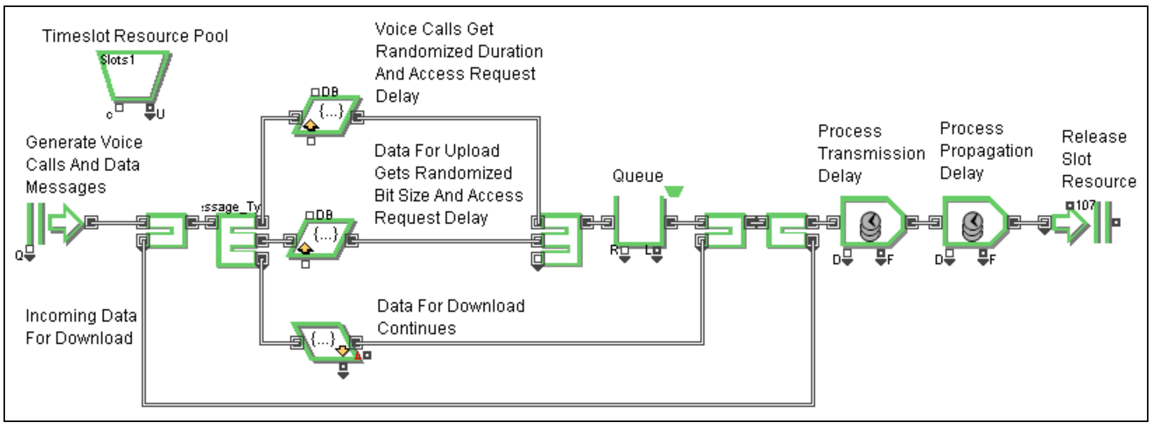

Figure 14. 5-kHz channel model element

The 5-kHz channel model element uses a first-in-first-out (FIFO) queuing process to handle the accumulation of demands for the 2.4 kbps service. As traffic flows from terminals into the system, the element checks to see if the 2.4 kbps access is available. If the access is available, it is allocated to the terminal user for a voice connection or for a data connection. The connection is occupied for the duration of the voice call or, in the case of data service, for a duration consisting of the upload and download time. One earth-satellite propagation delay of 0.25 seconds is also added to the actual voice and data transmissions. The UFO Extend™ model includes 20 of these 5-kHz channel elements in line with the simulation assumptions.

b. 25-kHz Channel Model Element

As discussed in Chapter III, a 25-kHz channel can support five 2.4 kbps accesses. Since this segmentation of the channel is most commonly used by the military in practice, all 25-kHz channels are modeled in this way. The 25-kHz channel model element is similar to the 5-kHz element with the following exceptions. Instead of a single

2.4 kbps resource to manage, the element has five such accesses to be distributed and reclaimed after use. The link set-up overhead delay for the 25-kHz channel model element is also accounted for based on previous research [31]. The 25-kHz channel uses shorter frames in its waveform, which results in shorter overhead delay in communicating with the NCT. In this case, a 0.5-second delay (two round trip propagation delays) and a delay value based on an exponential distribution with a mean of 0.5 seconds are added to every message transmitted over the 25-kHz channel. The actual structure of the 25-kHz element is the same as illustrated in Figure 14; only the parameters mentioned above are different. Again, terminals on a 25-kHz channel can only communicate with terminals on the same channel, and the UFO Extend™ model includes 20 of these 25-kHz channel elements.

2. MUOS Model

The MUOS network architecture and WCDMA waveform have been shown to be significantly different from those of the UFO system. The MUOS model reflects the differences. Since it is assumed that the JTF is operating under one MUOS spot beam, only four WCDMA carriers are available for use. This is likely a worst case scenario for MUOS, since an area of operation would have a high probability of at least being partially covered by multiple beams. Recall from Chapter III that each carrier is limited by the 494 channelization spreading codes that each has available for services. Each access consumes a certain number of codes based on the service data rate. Four WCDMA carrier elements are created as part of this MUOS model. This model assumes that all codes can be loaded onto the four carriers, which would use up a considerable amount of the satellite's power and limit the number of accesses that could be provided in the other 15 spot beams of the satellites footprint. However, given the importance of the mission of the JTF, this consequence is assumed to be acceptable. Figure 15 presents a diagram of a carrier element in the MUOS model.

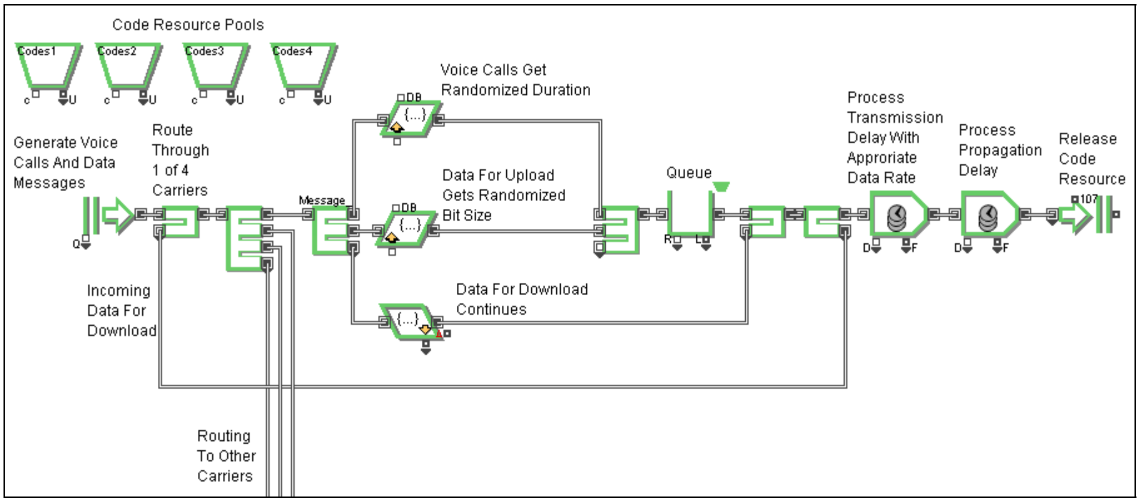

Figure 15. MUOS carrier model element

The model receives service requests from users and routes them to an available carrier element for allocation of the required codes from the carrier. Each carrier element contains a resource pool of 494 codes and a queue to hold waiting service requests. All carriers can provide access to a 2.4 kbps voice service (requiring one code) and data services of 9.6 kbps (requiring two codes), 32 kbps (requiring eight codes), and 64 kbps (requiring 16 codes). The model allows a data transmission to be uploaded by a sending terminal through one carrier at a certain rate and downloaded by a receiving terminal through a separate carrier at the same or differing rate. This characteristic simulates the various MUOS terminal data rate capabilities expected to be used on the system. The simulation assumes that 50% of demanded MUOS data services are at 9.6 kbps, 25% are at 32 kbps, and 25% are at 64 kbps. Because all MUOS transmissions require two earth-satellite propagation delays, a 0.5-second delay is added to all transmissions. Finally, the legacy payload outfitted on the MUOS satellite is not a part of the MUOS model, as this study is meant to compare a system of MUOS terminals operating with the WCDMA waveform against the legacy UFO system.

D. TRAFFIC GENERATION

The variables that make up the traffic demand include the number of terminals, the arrival rate of transmission requests, the duration of voice calls, the size of data messages, and the ratio of the number of voice calls to the number of data transmissions.

As part of the study, the UFO and MUOS system models are subjected to incremental levels of equal traffic loads. The load in total voice calls and data messages per time unit is denoted by arrival rate λ. All calls/messages are considered to be of the same precedence. Table 5 provides an example of the input parameters for one of the traffic loads used in the simulation.

	Channel		
Parameter	5-kHz	25-kHz	MUOS
Number of Terminals per Channel	8	17	500
Terminal Interarrival Time (sec)	600	600	600
Channel Interarrival Time (sec)	75	35.3	1.2
Terminal Arrival Rate (1/sec)	0.00167	0.00167	0.00167
Channel Arrival Rate (1/sec)	0.013	0.0283	0.833
Number of Channels	20	20	1
Arrival Rate for 20 5-kHz/25-kHz Channels (1/sec)	0.267	0.567	
Arrival Rate per System (1/sec)	0.833		0.833
Exponential Distribution Average Bit Size (bits)	36000	36000	36000
Exponential Distribution Voice Call Duration (sec)	30	30	30

Table 5. Traffic load input parameters

The simulation uses the exponential distribution for the generation of calls/messages. For this particular traffic load, the mean arrival rate per terminal is 0.00167; each terminal originates on average 0.00167 calls/messages per second or 1 call/message every ten minutes (600 seconds) on average. The voice call duration is based on an exponential distribution with a mean of 30 seconds. The data message size is also based on the exponential distribution with a mean of 36,000 bits. For the traffic load in Table 5, it is assumed that JTF communication planners utilizing the UFO system have pre-assigned eight terminals per 5-kHz channel and 17 terminals per 25-kHz channel. Under this configuration, the UFO system would be supporting 500 terminals (8 x 20 + 17 x 20). With 500 MUOS terminals generating traffic at the same individual rate of 0.00167, the total arrival rate in this particular traffic load for both the UFO and MUOS systems is 0.833 calls/messages per second.

The total demand imposed on the UFO model and that on the MUOS model are identical so that a direct comparison can be made. The total number of voice calls generated in the UFO model is the same as the total number of voice calls generated in the MUOS model at each load level. Similarly, the total number of data messages generated should be the same for each. The arrival rate can be adjusted by either adding/subtracting terminals on the systems or increasing/decreasing the time between arrivals.

E. SIMULATION AND METRICS

The performance investigation uses a Monte Carlo simulation of 500 runs, over a simulation period of five hours (18,000 seconds) per run, on each system model at each traffic load level. System performance under the varying load levels is determined by analyzing the following network metrics: total data message cycle time, voice call block rate, and channel utilization. The total data message cycle time accounts for all transmission delays and is the total time between a request by a sender to send a data message and the receipt of the entire data message by the receiver. The voice call block rate is the rate of calls that are unable to be made because of network congestion. Channel utilization is the proportion of the channel's resources actually used in transmitting the traffic.

Since each 5-kHz channel primarily handles data traffic, the simulation specifies that 90% of traffic originating from terminals on 5-kHz channels be data messages and 10% be voice calls. The simulation assumes that traffic on each system (UFO and MUOS) is 50% voice calls and 50% data messages. Table 6 shows the breakdown of the expected number of calls and messages for various levels of traffic load given these input parameters and a five-hour simulation run time.

	5-kHz	25-kHz	UFO	MUOS
System Traffic Load (0.417 messages/calls per second)				
Number of Voice Calls	240	3510	3750	3750
Number of Data Messages	2160	1590	3750	3750
System Traffic Load (0.833 messages/calls per second)				
Number of Voice Calls	480	7020	7500	7500
Number of Data Messages	4320	3180	7500	7500
System Traffic Load (1.67 messages/calls per second)				
Number of Voice Calls	960	14040	15000	15000
Number of Data Messages	8640	6360	15000	15000
System Traffic Load (2.5 messages/calls per second)				
Number of Voice Calls	1080	21420	22500	22500
Number of Data Messages	9720	12780	22500	22500
System Traffic Load (4 messages/calls per second)				
Number of Voice Calls	1200	34800	36000	36000
Number of Data Messages	10800	25200	36000	36000

Table 6. Expected number of calls and messages

Notice that, for the 5-kHZ channel, data messages always constitute 90% of the input traffic. The amount of voice calls and data messages generated is equal for both systems, and the total number of messages is equal across both systems for all traffic loads. Increased levels of traffic beyond those listed in Table 6 are also imposed on the MUOS model to examine the limits of the MUOS system.

F. DISCUSSION OF RESULTS

Data collection is started ten minutes into the simulation to allow for a warm up period. The averages for the prescribed performance metrics are calculated from the results of the 500 runs on each system model with equal traffic demand being incrementally applied.

1. Data Message Cycle Time

Figure 16 shows the data message cycle time for both systems as a function of the load.

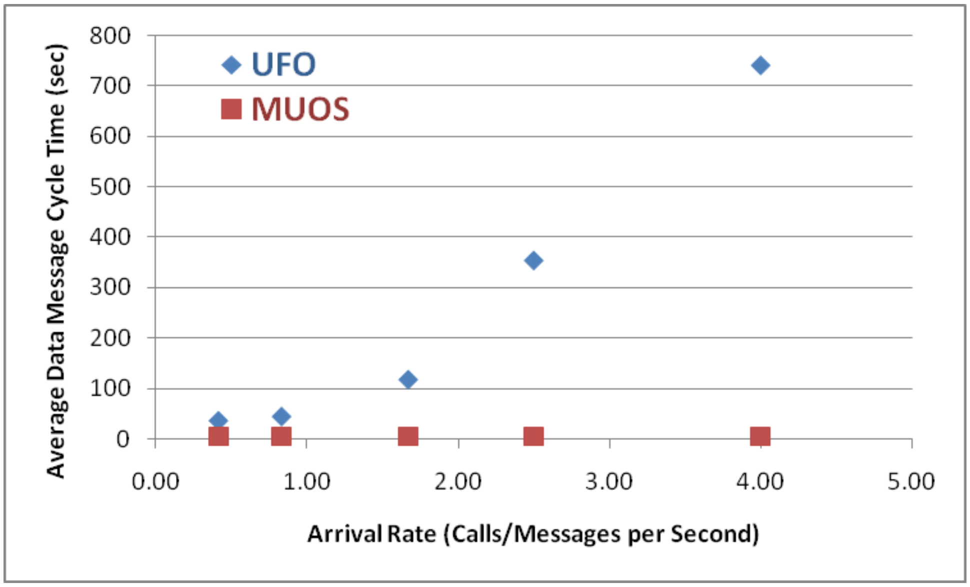

Figure 16. UFO and MUOS average data message cycle time

UFO data messages are disadvantaged compared to MUOS because they can only be transmitted over a 2.4 kbps data service. This leads to a greater contention for time slot resources and results in substantial queuing delay (i.e., waiting for transmission). As Figure 16 shows the average UFO data cycle time begins to increase drastically at around an arrival rate of 1.5 calls/messages per second, and at an arrival rate of four calls/messages per second, the UFO average cycle time is 741.3 seconds. Data messages averaging 36,000 bits would result in a throughput of 48.6 bits per second. This type of service would be unacceptable to the JTF. In contrast, the MUOS data message cycle times are all around 5 seconds, even for the 4 calls/messages per second arrival rate that UFO was unable to serve.

Figure 17, displaying the data message cycle time for MUOS as a function of the load, shows that MUOS data messages experience no queuing delay until demand inputs are increased beyond an arrival rate of 70 calls/messages per second.

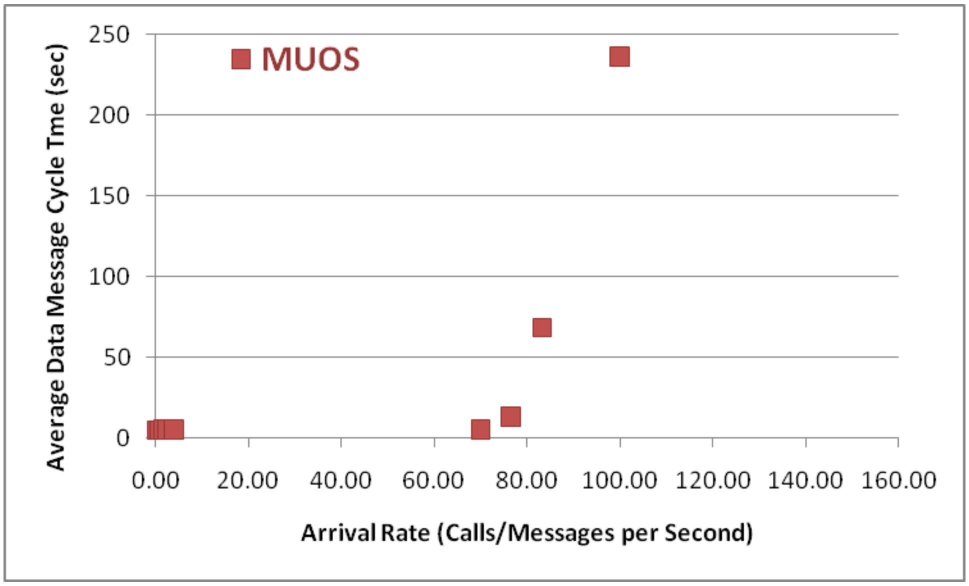

Figure 17. MUOS average message cycle time

For lower demand levels, the MUOS cycle time accounts for only the time required to upload and download (a function of the message size and both the upload and download user service data rates) and propagate back and forth from the earth to the satellite. With no queuing delay, there are no data messages waiting for spreading codes to become available. Under these conditions, the higher service data rates offered by MUOS result in much shorter message cycle times. These cycle times are consistently around five seconds for all arrival rates less than 70 calls/messages per second. As the arrivial rate execeeds a 70 call/message arrival rate, MUOS cycle time increases exponentially. Thus, MUOS can handle a much higher arrival rate than UFO can.

2. Voice Call Block Rate

For a tactical warfighter requiring voice communications in the field, nothing is worse than not being able to get through on the net. Call block rates should be kept to a minimum in order to provide as best assured access to forces as possible. Figure 18, displaying the simulation results for the voice call block rate metric, shows that the UFO model starts out meeting this requirement, but as the load increases, the block rate becomes unacceptable. For the arrival rate at a small value of 0.42 calls/messages per second, the UFO average block rate is already at 2%.

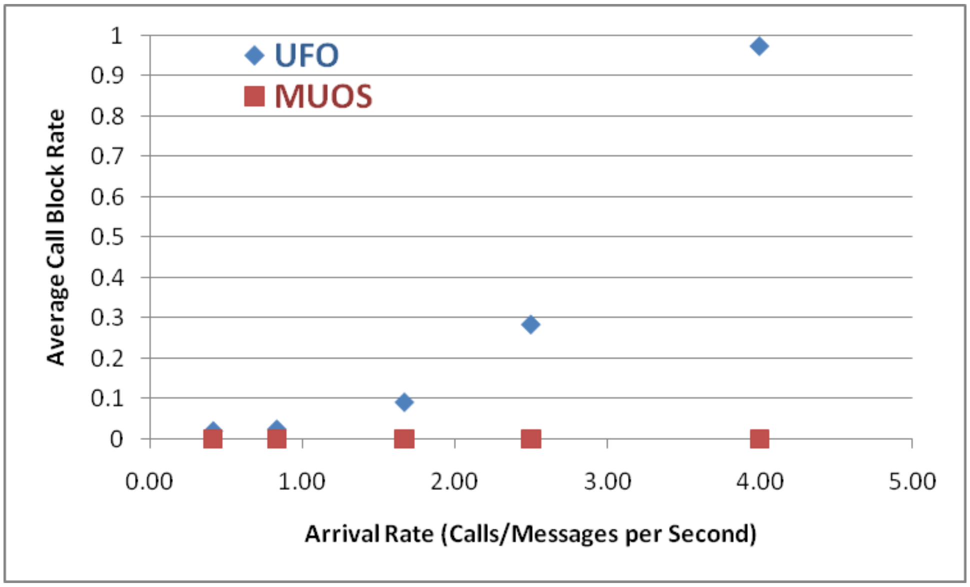

Figure 18. UFO and MUOS average call block rate

Continuing up to an arrival rate of 2.5 calls/messages per second, UFO suffers a 28.3% rate of voice calls being blocked. As the arrival rate reaches 4 calls/messages per second, unlike MUOS voice calls, virtually all UFO voice calls experience blocking and require some queuing time. Figure 19 shows the MUOS average call block rate.

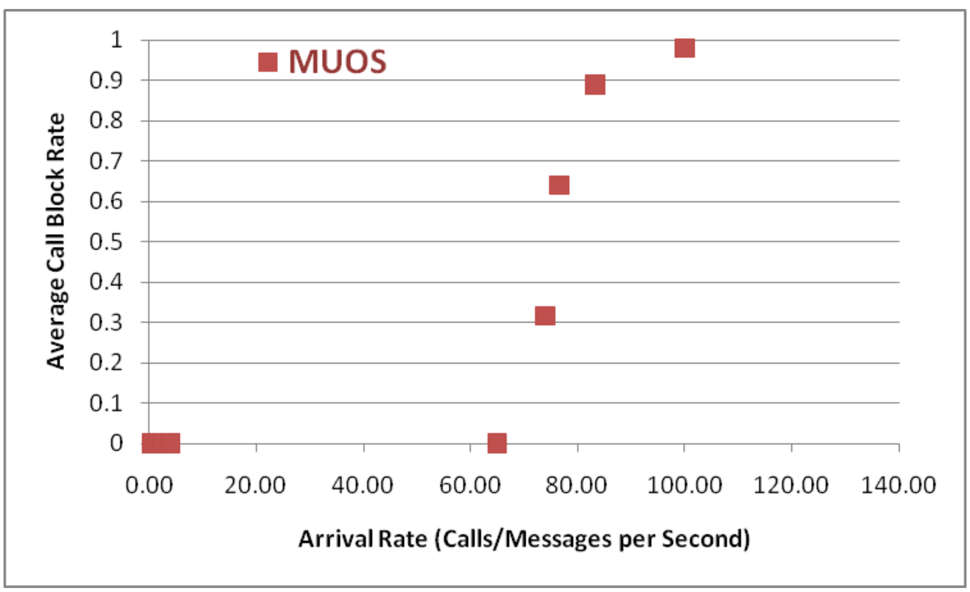

Figure 19. MUOS average call block rate

Figure 19 shows that MUOS does not experience any blocked calls at low traffic demands. For example, the call block rate is zero for arrival rates of 0.42, 0.83, 1.67, and 2.5 calls/messages per second. As the load increases, the MUOS model begins to show the occurrence of call blocking. All calls experience some blocking at the around the 100 calls/messages per second arrival rate. Call blocking at higher traffic demands does not mean that MUOS will be unable to provide appropriate service. MUOS offers a priority scheme (not modeled) with a preemption capability to provide guaranteed access to higher priority users if resources are in contention. This would be valuable to forces operating in conditions of high demand for MUOS resources.

3. Utilization

Network utilization is calculated on a per-channel (UFO) or per-carrier (MUOS) basis. Since the 5-kHz and 25-kHz channels manage a different number of resources and are subjected to different demands (different quantities of terminals assigned, ratio of voice calls to data calls, etc.), the utilization of each channel is determined separately. Figure 20 shows that the utilization of the 5-kHz channels increases towards complete utilization at roughly the 2.5 overall system messages/calls per second arrival rate.

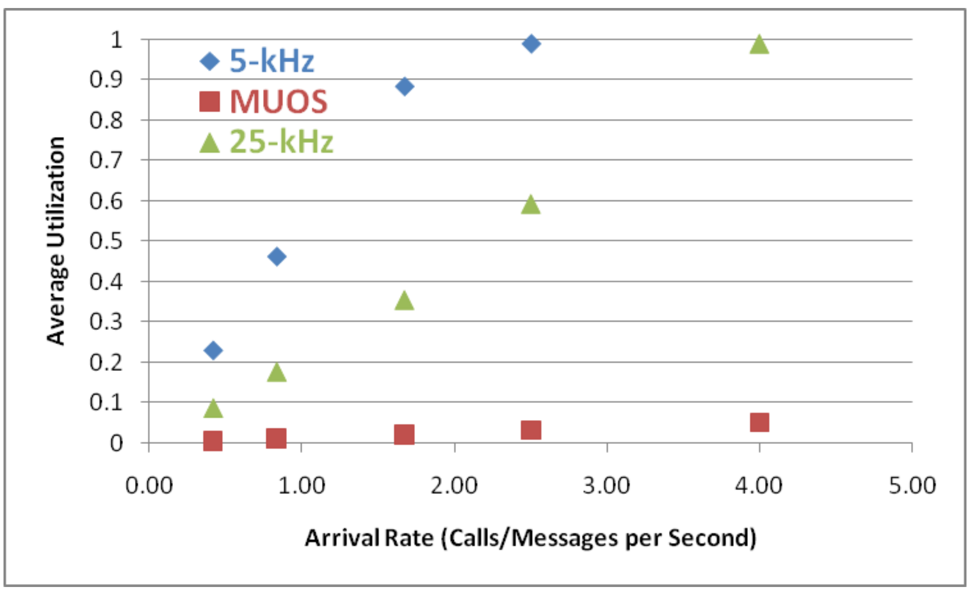

Figure 20. Average channel utilization

The entire UFO model saturates as the arrival rate approaches 4 calls/messages per second. Conversely, the MUOS model shows no signs of stress for any of these low arrival rates (i.e., up through 4 calls/messages per second). For example, the utilization of a carrier in the MUOS model starts at 0.5% for an arrival rate of 0.42 calls/messages per second and increaes to roughly 5% at an arrival rate of 4 calls/messages per second.

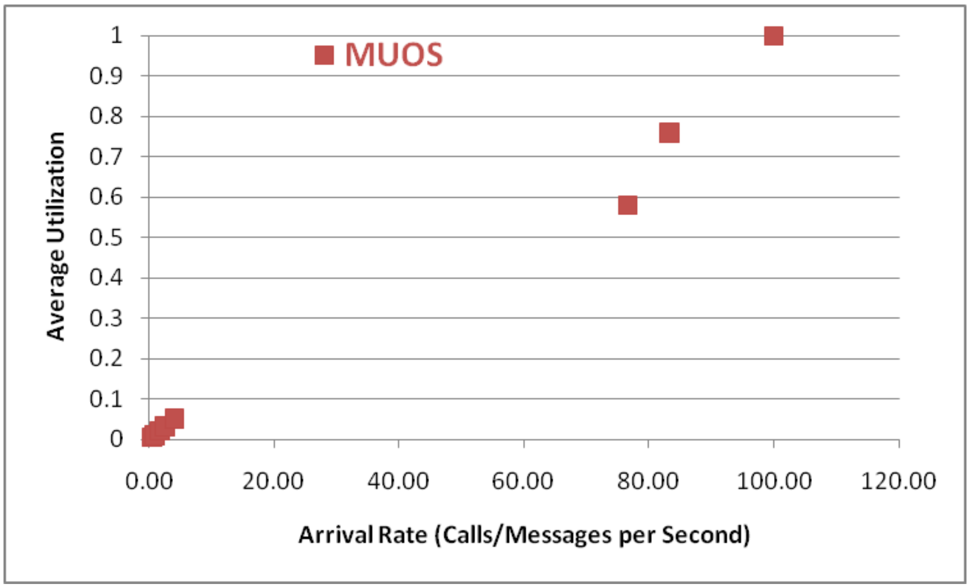

Figure 21. MUOS carrier average utilization

Figure 21 shows that MUOS utilization increases to saturation around the 100 call/messages per second traffic rate, well beyond the saturation point of the UFO model. These utilization results are as expected given that one MUOS carrier can be thought of as having 494 resources of 2.4 kbps services, whereas a 25-kHz DAMA channel has five such resources, and a 5-kHz DAMA channel has only one.

Finally, a graph of MUOS carrier utilization over time is shown in Figure 20 for the MUOS model operating under one of the highest levels of demand inputs (83.3 calls/messages per second). Figure 20 shows a steady utilization of around 75%. A demand rate of 83.3 calls/messages per second could represent 5,000 terminals each with an individual mean time between calls of 60 seconds. While this type of demand may be beyond the needs of a current JTF, it is important to field a system that can also meet

demands of the future. As illustrated in Figure 19, the simulation results show that this level of demand could be supported because it results in a steady level of utilization and provides enough margin to respond to any sudden spikes in demand.

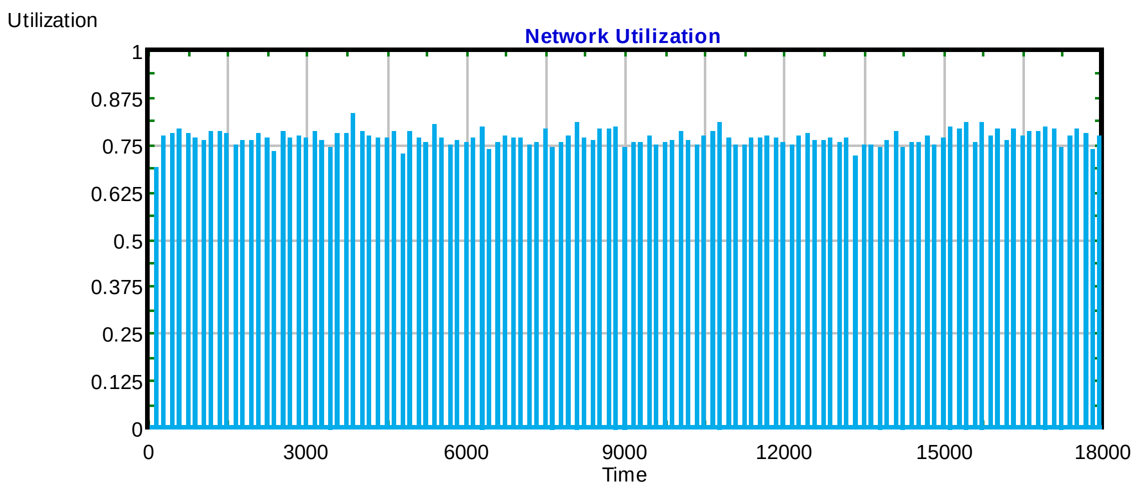

Figure 22. MUOS utilization over time given 83.3 calls/messages per second demand

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V. CONCLUSIONS AND FUTURE RESEARCH

A. RESEARCH SUMMARY

This research aims to compare the system performance and capabilities of the UFO and MUOS systems in supporting a hypothetical JTF in terms of the number of users supported and the quality of service provided. The importance of UHF MILSATCOM to the tactical warfighter is first highlighted. An in-depth look at the capabilities and available services of each system is undertaken. Modeling and simulation based on each system's network architecture, as described in Chapter III, is then used in the conduction of the performance comparison.

B. KEY FINDINGS

For the prescribed JTF operational scenario, MUOS can tolerate a traffic demand rate of about 83 calls/messages per second where UFO saturates at roughly 4 calls/messages per second. MUOS achieves this leap in system performance by not only providing more resources, but also by using the power of WCDMA technology to pool those resources together for dynamic on-demand allocation vice the UFO static assignment of channels to users that do not take full advantage of them. This enhancement allows for maximum simultaneous usage and is what lends to the point of developing MUOS satellites vice simply launching more UFO satellites. MUOS's faster data rate services (9.6 kbps, 32 kbps, and 64 kbps vice UFO's 2.4 kbps) contribute significantly to shorter data message cycle times. This in turn provides a higher quality of service to users, allows them to share larger amounts of data, and relieves congestion on the network. MUOS allows users to communicate seamlessly with any user around the world, while UFO restricts users to their assigned channels and generally serves users in the same satellite coverage area.

C. FUTURE RESEARCH

The comparison conducted in this study spawns a number of further areas of study and research. They are:

- Developing a worldwide model of both systems for simulation against the traffic demands of various major theatres of war.
- Incorporating satellite power and mutual access interference limitations into any worldwide MUOS model.
- Analyzing the improvement in UFO system performance from the use of recently introduced terminals in compliance with the IW standards.

D. CONCLUSION

MUOS's ability to offer a higher level of quality of service, assured access, and increased capacity translates to more tactical users sharing timely information without the worry of not getting through to their intended recipient. Faster service data rates reduce delays in relaying information during time critical operations. MUOS also fosters collaboration and information networking by providing the ability to use MUOS terminals as connection points to the NIPRNET and SIPRNET, which UFO cannot presently do. The system represents a paradigm shift in UHF SATCOM from circuit-based, assigned networks to on-demand, global IP-based, net-centric networks. This study has shown that, as specified in its designs, MUOS can provide a level of system performance that will place the system in a preeminent role for the NCO critical to the mission effectiveness of today's military.

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